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Effect of contact pressure on wear and friction of ultra-high molecular weight polyethylene in multi-directional sliding

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ABSTRACT

Computational wear models need input data from valid tribological tests. For the wear model of total hip prosthesis, the contact pressure dependence of wear and friction of ultra-high molecular weight polyethylene (UHMWPE) against polished CoCr in diluted calf serum lubricant was studied, and useful input data produced. Two test devices were designed and built, heavy load circularly translating pin-on-disk (HL-CTPOD) wear test device and HL-CTPOD friction measurement device. Both can be used with a wide range of loads. The wear surface diameter of the test pin was kept constant, 9 mm, whereas the load was varied so that the nominal contact pressure ranged from 0.1 MPa to 20 MPa. The wear factor decreased with increasing contact pressure, whereas the coefficient of friction first increased with increasing contact pressure with low pressure values, and then decreased. Up to the pressure of 2.0 MPa, the wear mechanisms and wear factors were in good agreement with clinical findings. In the critical range of 2.0–3.5 MPa, the wear mechanisms and wear factors started to differ from clinical ones, and the decrease of the wear factor steepened. The discrepancy became more and more evident as the pressure was gradually increased beyond 3.5 MPa. It appears that the pressure value of 2.0 MPa should not be exceeded in pin-on-disk wear tests that are to reproduce the clinical wear of UHMWPE acetabular cups.

Keywords: wear, friction, contact pressure, ultra-high molecular weight polyethylene, pin-on-disk

1 INTRODUCTION

In earlier studies, Saikko and Calonius presented the first verified computations of the kinematics of the prosthetic hip joint illustrated as so-called slide track patterns [**1–4**]. Moreover, they proved the importance of the slide track shape for the wear produced [**5**]. A slide track is the track of an arbitrary point of the bearing surface drawn on the counterface by the cyclic relative motion, such as that taking place in walking, the most important activity as regards wear. The wear factor of ultra-high molecular weight polyethylene (UHMWPE) was shown to steeply decrease with increasing aspect ratio (AR) of the slide track figure [**5**]. In the present paper, the effect of the contact pressure on the wear and friction of UHMWPE was studied with the established circularly translating pin-on-disk (CTPOD) test principle [**6**] using polished CoCr as the counterface and diluted calf serum as the lubricant. Early work on this subject was done with unidirectional sliding [**7–9**], which does not represent the clinical conditions as well as multi-directional sliding [**10,11**] with respect to wear mechanisms. A typical finding is that the wear factor decreases with increasing contact pressure [**9–11**]. The existing 12-station [**12**] and 100-station [**13**] CTPOD devices were modified so that the load could be varied over a wide range, the diameter of the test pin, 9 mm, and all other test parameters remaining unchanged. The effect of both the AR and the contact pressure on wear are needed as input for a realistic computer model of the prosthetic hip wear.

2 MATERIALS AND METHODS

To study the effect of the nominal contact pressure $p = L/A_{ws}$, where L is the load and A_{ws} is the wear surface area of the pin, on the wear of UHMWPE, the existing 100-station Super-CTPOD hip wear simulator [**13**] was modified so that in one test station, L could be substantially increased. The established parameters are L = 70.7 N, A_{ws} = 63.6 mm^2, and p = p_{ref} = 1.1 MPa. It was considered important to change specifically L and keep all other key parameters, such as A_{ws}, lubricant bulk temperature and volume, etc., unchanged, instead of increasing p the easy way by decreasing A_{ws}, because this could give misleading results [**14**]. The Super-CTPOD has a robust structure and an efficient temperature control system making it an excellent base for the HL-CTPOD modification. With high friction power, effective cooling is needed to avoid overheating of the specimens and of the lubricant, which could make the wear mechanisms quite different from those occurring in vivo. The motion module and the temperature control system of the Super-CTPOD design were utilized as such. The pin guiding and loading were redesigned for heavy load testing. The pin was guided by a linear bearing and loaded by weights (Fig. 1). Exclusive of L, the test conditions were kept as close as possible to those in st.1 of the modified 12-station CTPOD that was used to study the effect of the slide track aspect ratio on the wear factor [**5**]. Friction vector rotated about the load axis 1 r/s, contact was flat-on-flat, diameter of the cylindrical pin 9.0 mm, sliding speed 31.4 mm/s, slide track dia. 10.0 mm, lubricant bulk temperature 24 ± 1 ºC, volume 12 ml, composition HyClone Alpha Calf Fraction serum SH30076.03 diluted 1:1 with distilled water so that the protein concentration was 21 mg/ml, pin material Sulene-PE (GUR 1020, γ-sterilized in N_2), and counterface polished CoCr. The load used in the tests varied from 16 N to 700 N yielding p values from 0.25 MPa to 11 MPa. However, the last test was finished with an extreme value of p = 20 MPa, the second highest value being 11 MPa. The gravimetric wear rate $\dot{w}$ was calculated by dividing the weight loss of the pin with the number of cycles, which was 85 000 on the average with each p value. This value was corrected with the weight gain of the unloaded soak control pin. The tests were run with ascending p value order. After each 24 h run, the specimens and their holders were disassembled and cleaned, and the pin was weighed, after which the test was continued with the next higher p value and fresh lubricant. The linear wear rate $\dot{h} = \dot{w}/\rho A_{ws}$, where ρ is the density, 0.93 mg/mm^3. The wear factor $k = \dot{w}/\rho Ls$, where s is the sliding distance. Each of the 6 wear tests was done with a new pin. Before the actual tests, the pin was run in with the lowest load until the maching marks were completely removed and the entire wear face was polished. This took several days with p = 0.25 MPa, but only 24 hours with p = 1.1 MPa.

One station of the existing 12-station CTPOD device [**12**] was redesigned for friction measurements with a wide range of loads (Fig. 2). The loading arrangement was identical to that of the HL-CTPOD wear test device. The test disk was fixed to the upper end of a vertical shaft supported with low-friction ball bearings. The rotation of the shaft was prevented with a horizontal bar with 25 mm distance from the vertical axis. The bar was pushed by a shoulder in the plate to which the test disk was fixed, the plate forming the upper end of the shaft. The bar was fixed to a horizontal low-friction linear bearing, the movement of which was prevented by a small force tranducer. The pushing force was generated by the friction between the pin and the disk. From the signal of the calibrated transducer-amplifier system, the coefficient of friction could be calculated. Since the slide track radius was 5 mm and the load limit of the transducer was 30 N, the maximum friction force that could be measured was 30 N × 25 mm / 5 mm = 150 N. The test chamber was surrounded by a cooling water basin so that the serum temperature could be kept constant. The specimens and all test conditions including the lubricant were similar to those in the wear tests. The measurement procedure was as follows. The pin was run in for 24 hours with 1.1 MPa. Then the load was increased stepwise, starting from the minimum value. With each p value, the average value of the signal during a cycle was recorded with a digital oscilloscope after a certain running time. This time was 60 min in tests 1 and 2, 30 min in test 3, and 5 min in tests 4 to 7. The running time was kept relatively short to minimize the effects of serum degradation on friction. Complete levelling out of the signal after the increase of load could not be required. Wear tests have shown that if several days are run with the same serum, friction may decrease for days due to serum degradation [**12,14**].

3 RESULTS

In wear test 1, it was found that the contact pressure dependence of the wear rate was weak (Fig. 3). Above 2.3 MPa, the wear face of the pin showed protuberances (Fig. 4) which are not typical of cups removed from patients. In test 2, the range 1.1–4.0 MPa was therefore studied in more detail. It was found that $\dot{w}$ showed a peak coinciding with the appearance of the protuberances. Tests 3–6 covered p values from 0.25 to 11 MPa and confirmed this trend. In general, the protuberances appeared within the p range of 2.0–3.5 MPa, and $\dot{w}$ increased with increasing p as long as the protuberances were absent. When they appeared, $\dot{w}$ stopped increasing or decreased with increasing p. When p was below 2.0 MPa, the wear face never showed protuberances, being polished to a mirror finish (Fig. 5a,b). Above 3.5 MPa, the wear face always showed protuberances, the size of which increased with increasing p (Fig. 5c,d). In the extreme test with p = 20 MPa, the wear rate was equal to that with p = 11 MPa. It was common for all 6 tests that k decreased with increasing p, and the decrease steepened after the protuberances appeared (Fig. 6). The following power relationships were obtained for pooled data:

$$k = 2.7 \times 10^{-6}(p/p_{\mathrm{ref}})^{-0.57}\ \mathrm{mm^3/N\ m}\ (r^2 = 0.88),\ \text{when}\ p/p_{\mathrm{ref}} \leq 2.53 \quad (1)$$

$$k = 6.0 \times 10^{-6}(p/p_{\mathrm{ref}})^{-1.44}\ \mathrm{mm^3/N\ m}\ (r^2 = 0.84),\ \text{when}\ p/p_{\mathrm{ref}} > 2.53 \quad (2)$$

Below $p_{\mathrm{ref}} = 1.1$ MPa, the coefficient of friction μ first increased with increasing p, reached a peak by p_{ref} or earlier, and then decreased (Fig. 7). The following power relationship was obtained for pooled data:

$$\mu = 0.32 \times (p/p_{\mathrm{ref}})^{-0.68}\ (r^2 = 0.88),\ \text{when}\ p/p_{\mathrm{ref}} \geq 1 \quad (3)$$

The CoCr disks were not scratched or otherwise damaged in the wear and friction tests, retaining their original mirror finish.

4 DISCUSSION

Below the nominal contact pressure value of 2.0 MPa, the polyethylene wear surface was burnished, which is in agreement with acetabular cups removed from patients [**15**]. With p = 1.1 MPa, the established CTPOD p_{ref} value, the wear factor was 2.7×10^{-6} mm^3/N m, remarkably close to the average clinical wear factors measured for the classic Charnley design, 2.9×10^{-6} mm^3/N m [**16**] and 2.1×10^{-6} mm^3/N m [**17**]. Above 2.0 MPa, however, the wear surface showed protuberances, which are not typical of clinical wear, and the wear factors were far below clinical values. Protuberances have been observed in polyethylene acetabular cups worn in a hip simulator using a peak load of 3 kN [**18**]. It appears therefore that 3 kN, stipulated in the ISO 14242-1 standard [**19**], is too high. This was observed also in the HUT-4 hip joint simulator, but the problems disappeared when the peak load was reduced to 2 kN [**20**]. The protuberances are possibly indicative of an overheating phenomenon leading to the toughening of the material. This could explain why the wear rate does not increase with increasing p above 3.5 MPa. Although the lubricant bulk temperature was forced to stay at 24 ± 1 ºC, the contact spots (protuberances) may still have overheated. The finding is in agreement with the earlier CTPOD observation that when A_{ws} was increased from 7 mm^2 to 62 mm^2, L remaining unchanged, 70.7 N, k increased tenfold, although p dropped from 10 MPa to 1.1 MPa [**14**]. The protuberance formation was heavy with 10 MPa [**14**]. A similar dependence of k on p was later observed in another pin-on-disk study [**10**], and in hip simulator tests, in which k increased with decreasing clearance [**11**]. Protuberances have been observed even with p = 1.1 MPa when the protein concentration of the lubricant was below the critical limit of 20 mg/ml [**21**]. In the other pin-on-disk study [**10**], the increase of p from 3.5 to 7.0 MPa, A_{ws} remaining unchanged, did not change $\dot{w}$ significantly. In the present study, a similar increase in p resulted in a clear decrease in $\dot{w}$. The type of polyethylene, counterface and serum among other variables are likely to affect the formation of protuberances. Hence, one must naturally be cautious in the generalization of the present results. Nevertheless, it appears that to minimize the risk of producing wear that differs from the clinical wear, the value of 2.0 MPa should not be exceeded in hip wear testing of UHMWPE. Note that the CTPOD principle has been shown to produce wear highly similar to the clinical wear of total hip prosthesis with p = 1.1 MPa [**5, 6, 12–14, 21**]. Especially in the Charnley design with an exceptionally small head diameter, 22 mm, the contact pressures are likely to exceed 3.5 MPa. Still, protuberances are not found [**15**]. One possible reason for this discrepancy is that the sliding in the laboratory is continuous and repeats the same cycle again and again. This differs from the clinical situation. With respect of wear rate, the present results indicate that p values in the critical zone, where the transition of the wear mechanisms occurs, are more harmful than higher values because the wear rate reaches its maximum at 2.0–3.5 MPa (Fig. 3). This finding is in agreement with clinical ones showing that volumetric wear rate increases with increasing head diameter [**22**]. In contrast to the common belief, the difference in sliding distance is irrelevant. It was shown with a hip simulator that the wear rate is independent of the sliding distance per cycle [**23**].

In wear tests, the degradation of serum is known to reduce the wear rate through the precipitation of proteins resulting in the formation of anti-wear protein slurry [**24**]. This does not occur in vivo. The smaller role of degradation could explain why the wear factors in the present 85 000 cycle tests were higher than those in the earlier, otherwise similar tests running 500 000 cycles with the same serum, 2.7×10^{-6} mm^3/N m vs. 1.6×10^{-6} mm^3/N m on the average with $p = 1.1$ MPa [**13**]. This difference is in agreement with another pin-on-disk study [**10**], where it was found that reducing the lubricant change interval increased the wear rate. The same effect can be achieved also by increasing the lubricant volume [**24**]. This suggests that the key factor is the amount of precipitated protein relative to the amount of soluble protein. Precipitated protein decreases $\dot{w}$ and the soluble protein increases $\dot{w}$. In the course of the test, the serum becomes cloudy due to protein precipitation and other denaturation and degradation phenomena. The high cost of serum and the amount of work in disassembly, cleaning, wear measurement and reassembly puts a certain lower limit to the serum change interval. In principle however, the more frequent the change is, the more truthful the measured $\dot{w}$ and μ values should be. On the other hand, when the interval is short, the weight change to be quantified is small, which causes problems in measurement uncertainty and repeatability of results (Fig. 3). Usually, the serum change interval in published studies is 250 000–500 000 cycles, that is, 3–6 days.

It seems that the protein slurry reduces not only wear but also friction. As the degradation effects in the present tests were minimal compared with long duration tests, the measured μ values were much higher than those measured in longer tests. For example, the coefficient of friction in the present tests was 0.26–0.34 with 1.1 MPa, while it was as low as 0.05 after several days of running in the earlier wear tests [**12,14**]. At low p values, mixed lubrication mechanism probably prevailed, as μ increased with increasing p. On the other hand, above 1.1 MPa, the decrease of μ with increasing p suggested dry sliding. No polyethylene transfer to the counterface occurred, however, indicating that boundary lubrication by proteins was active.

The effect of AR on k is known from the earlier study [**5**]. The effect of p and AR, assuming that they are separable, on k can now be expressed as:

$$k = 2.7 \times 10^{-6}(p/p_{\mathrm{ref}})^{-0.57}\mathrm{AR}^{-0.49}\ \mathrm{mm^3/N\ m},\ \text{when}\ p/p_{\mathrm{ref}} \leq 2.53 \tag{4}$$

$$k = 6.0 \times 10^{-6}(p/p_{\mathrm{ref}})^{-1.44}\mathrm{AR}^{-0.49}\ \mathrm{mm^3/N\ m},\ \text{when}\ p/p_{\mathrm{ref}} > 2.53 \tag{5}$$

where p_{ref} = 1.1 MPa. The above k_{ref} values, 2.7×10^{-6} mm^3/N m and 6.0×10^{-6} mm^3/N m, are from the present study because the running time with the same serum was lower than that in the AR study [**5**]. In the latter, k_{ref} was found to be 1.9×10^{-6} mm^3/N m with p = 1.1 MPa and AR = 1. The present tests were done to provide future computer models with realistic input data. Therefore, the models would not need to be based on the unfounded simplification that k is a constant. With a validated computer model, the study of the effects of several important variables on wear is much easier compared with hip simulator tests that are laborious, time-consuming and expensive. These variables include the type of relative motion and load, diameter, initial clearance, cup thickness and modulus. Pin-on-disk test results with more repetitions and longer durations, and with varying slide track shape and contact pressure can be incorporated in the model when available. It is essential to understand that computer simulations can be highly misleading if they do not use valid input from valid wear tests. In a realistic computer model, the k value is scaled in each computation point according to the slide track shape and the contact pressure. The direction of the resultant joint force in walking may continually vary relative to the femoral head and to the acetabular cup [**25**]. Consequently, the location and size of the contact zone change all the time. The contact pressure distribution is influenced also by the variation in the magnitude of the resultant force, and by the creep. Hence, k must be updated, say, 100 times during the cycle according to the variation of the contact pressure with time and with location on the bearing surface. Computer models of the acetabular cup wear developed so far [**26**–**29**] are deficient in the sense that they omit the slide track shape. They involve the sliding distance only, as if the multidirectionality of the motion did not affect the wear at all. They take k as a constant, although it is, in fact, highly variable with the slide track shape [**5**] and with the contact pressure. Morever, they assume that the wear depth per cycle depends linearly on p. Fig. 3 clearly shows that this is not the case, especially above p = 2.0 MPa. One could justify the use of a constant k in a wear model by reasoning that k contains the local variation of slide track shape and pressure. The value is, after all, calculated from the gravimetric or volumetric wear of the entire bearing surface. However, such a model can, at its best, be valid only for the specific hip simulator wear test from which the k value is taken. It cannot be applied to any another case because the total wear contains not only the effect of the slide track pattern and load profile, but also the effect of all other variables specific only for the test in question. This makes a model based on a constant k of very limited use. The pin can be considered a finite element, with which the effect of fixed AR and pressure values on wear can be studied. The results can then be applied to the ball-in-socket case having a wide range of slide track shapes and pressure values. These are both are location-dependent, and *p* also time-dependent.

In earlier tests simulating the wear of the total knee prosthesis [**30**], contact pressures were almost 20 MPa. Despite the high *p* values, there were no protuberances. This is probably due to the fact that in the knee, the contact zone moves substantially and cyclically relative to the tibial plate. In the acetabular cup, the contact zone is more stationary. Consequently, the wear mechanisms in the knee are fundamentally different from those in the hip.

5 CONCLUSIONS

The UHMWPE wear factor was shown to steeply decrease with increasing contact pressure. On the other hand, the wear rate and coefficient of friction first increased and then decreased with increasing contact pressure. It is important to include these relationships in future computer wear models of the total hip replacement, together with the dependence of the wear factor on the slide track aspect ratio. It seems that to be on the safe side, the contact pressure value of 2.0 MPa should not be exceeded in pin-on-disk wear tests of UHMWPE, if clinical wear of acetabular cups is to be reproduced. This is because only up to the critical pressure of 2.0 MPa, the wear mechanisms were always in agreement with the clinical ones, and the wear factors sufficiently high in comparison with clinical findings.

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NOTATION

AR	aspect ratio
A_{ws}	area of wear surface of test pin
CTPOD	circularly translating pin-on-disk
$\dot{h}$	linear wear rate
HL-CTPOD	heavy load circularly translating pin-on-disk
k	wear factor
k_{ref}	reference wear factor
L	load
p	nominal contact pressure
p_{ref}	reference nominal contact pressure
s	sliding distance
UHMWPE	ultra-high molecular weight polyethylene
$\dot{w}$	gravimetric wear rate
μ	coefficient of friction
ρ	density

CAPTIONS TO ILLUSTRATIONS

Fig. 1. HL-CTPOD wear test device, (a) general view, (b) close-up of test chamber and linear bearing of pin guiding. Device shown without lubricant and cooling water.

Fig. 2. HL-CTPOD friction measurement device, (a) general view, (b) close-up of friction force measurement system. Note cooling water bath surrounding test chamber.

Fig. 3. Gravimetric and linear wear rate of UHMWPE pins vs. contact pressure. Above critical pressure wear mechanisms differed from those seen clinically.

Fig. 4. Optical micrographs from the edge of worn UHMWPE pin showing protuberances. Nominal contact pressure was 10.7 MPa.

Fig. 5. Optical micrographs of worn UHMWPE pins. The nominal contact pressure was (a) 0.25 MPa, (b) 1.1 MPa, (c) 3.5 MPa, and (d) 10.7 MPa. The polished appearance in (a) and (b) is in agreement with clinical observations, whereas the protuberances in (c) and (d) are not.

Fig. 6. Wear factor of UHMWPE pins vs. relative contact pressure. p_{ref} = 1.1 MPa.

Fig. 7. Coefficient of friction vs. relative contact pressure of UHMWPE pins sliding against polished CoCr disks in diluted calf serum lubricant. p_{ref} = 1.1 MPa.

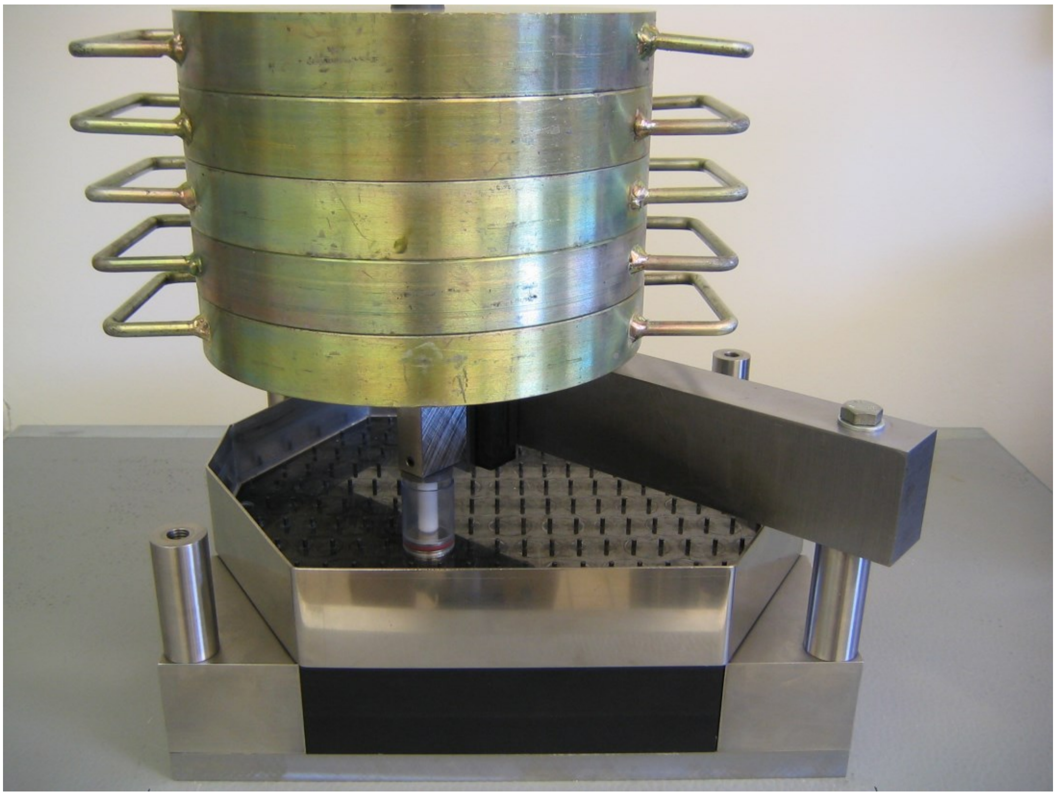


Fig. 1 (a)

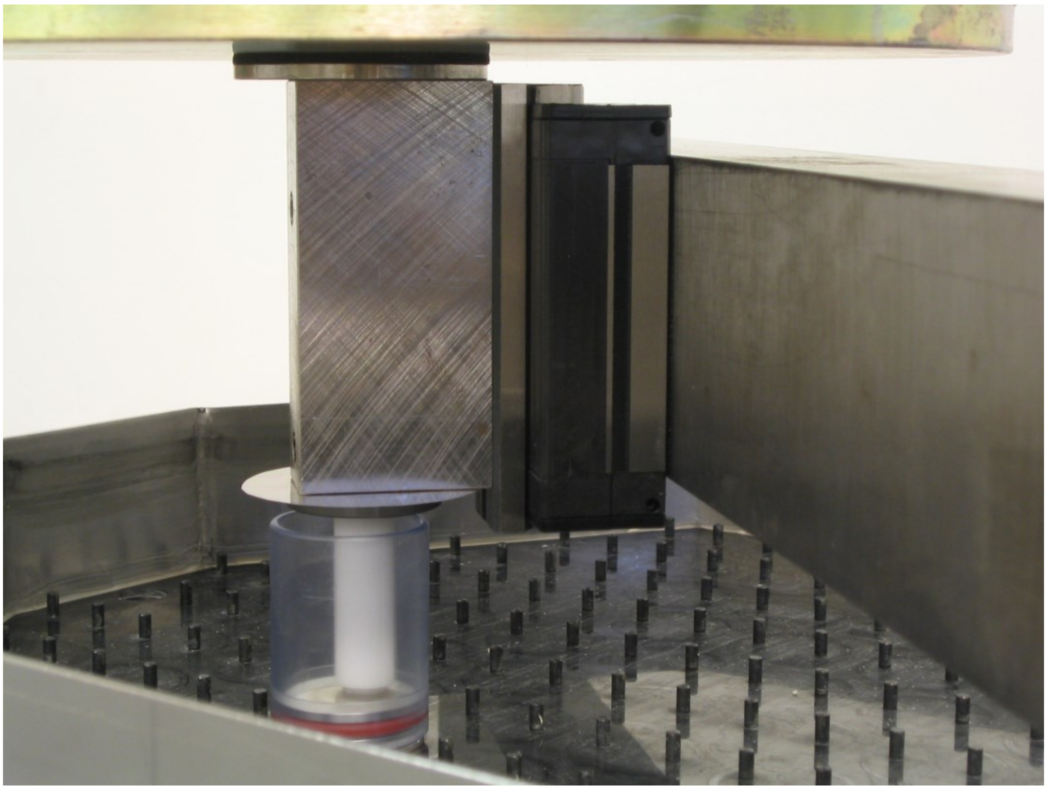


Fig. 1 (b)

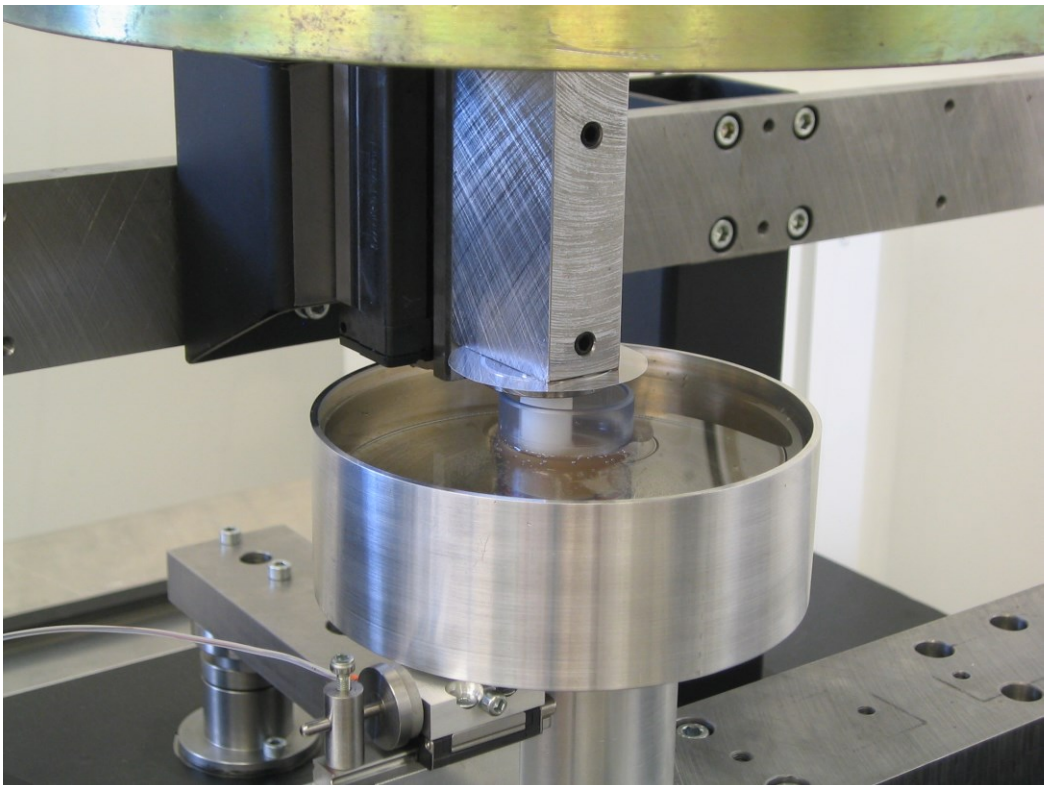


Fig. 2 (a)

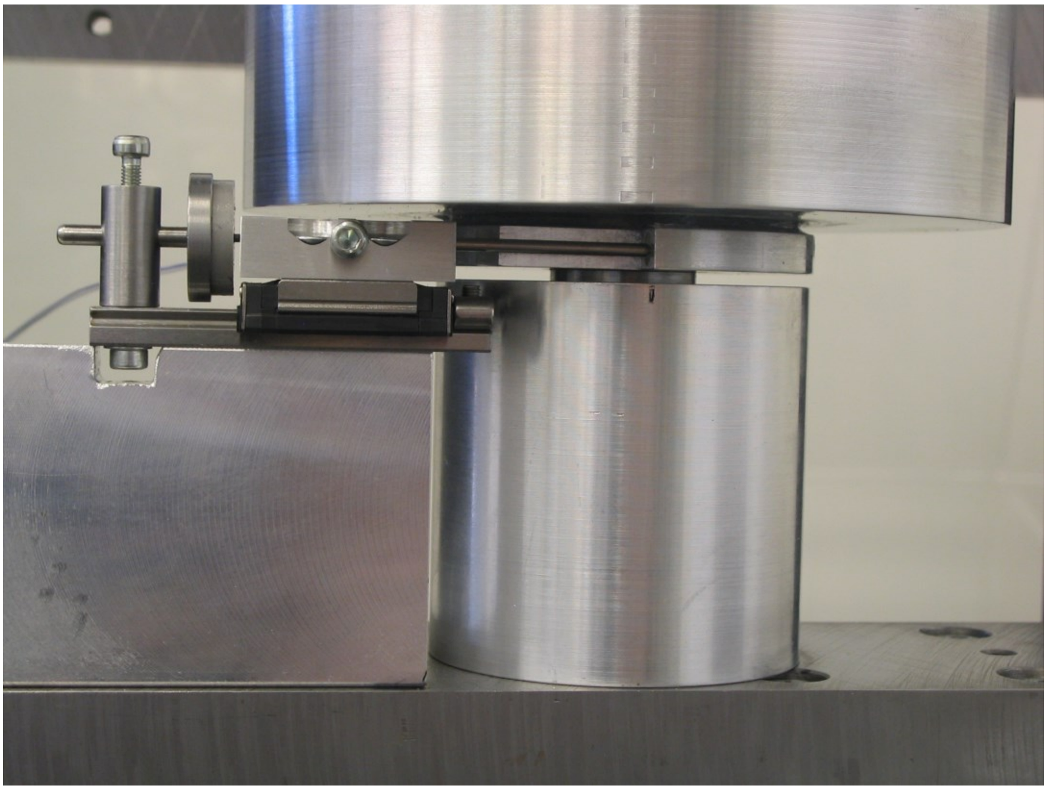
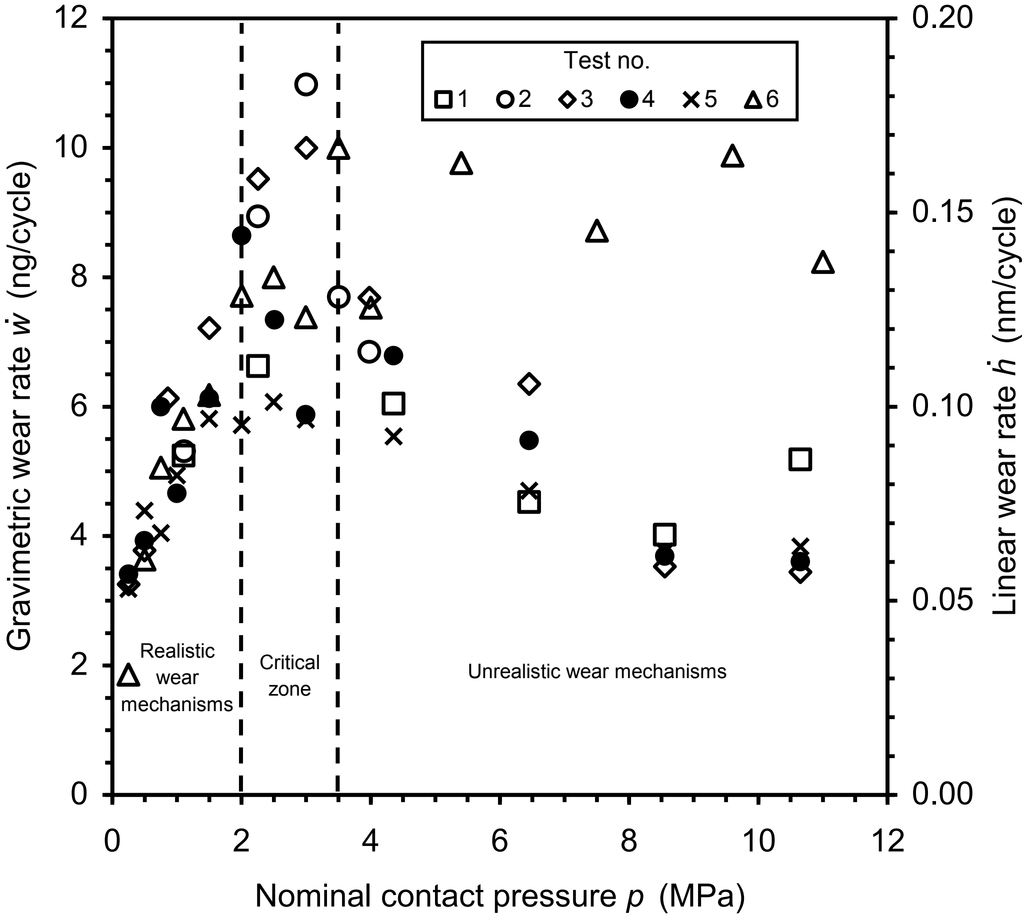


Fig. 2 (b)



Test no.
1
2
3
4
5
6
Realistic wear mechanisms
Critical zone
Unrealistic wear mechanisms
Gravimetric wear rate $\dot{w}$ (ng/cycle)
Linear wear rate $\dot{h}$ (nm/cycle)
Nominal contact pressure p (MPa)

Fig. 3

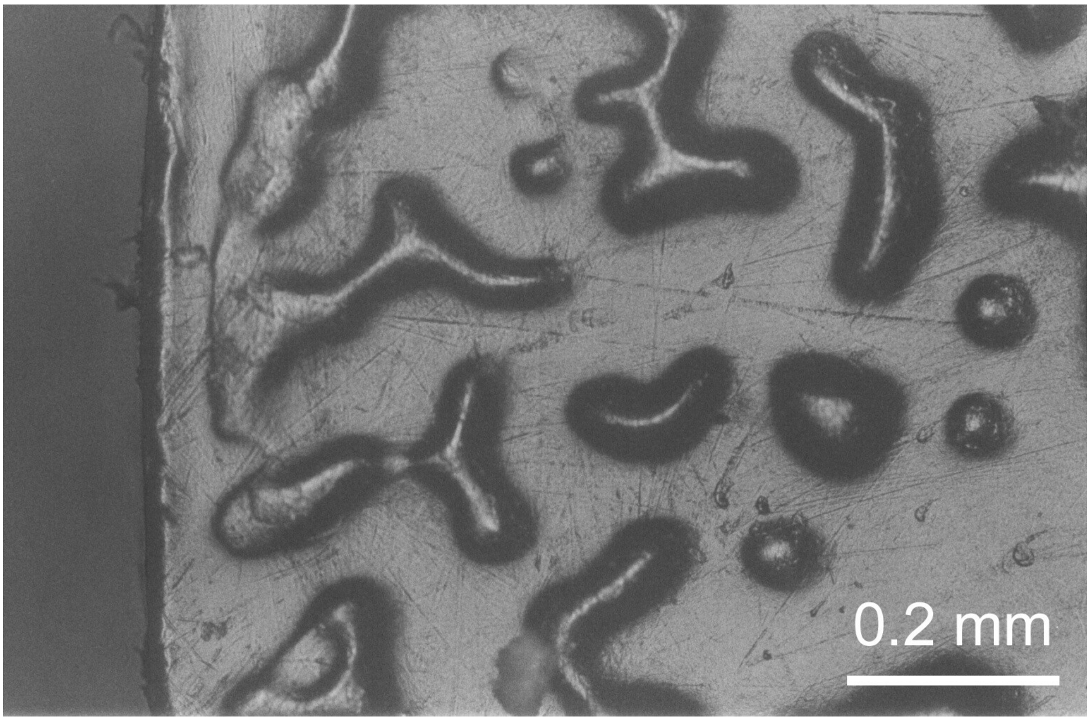


Fig. 4 (a)

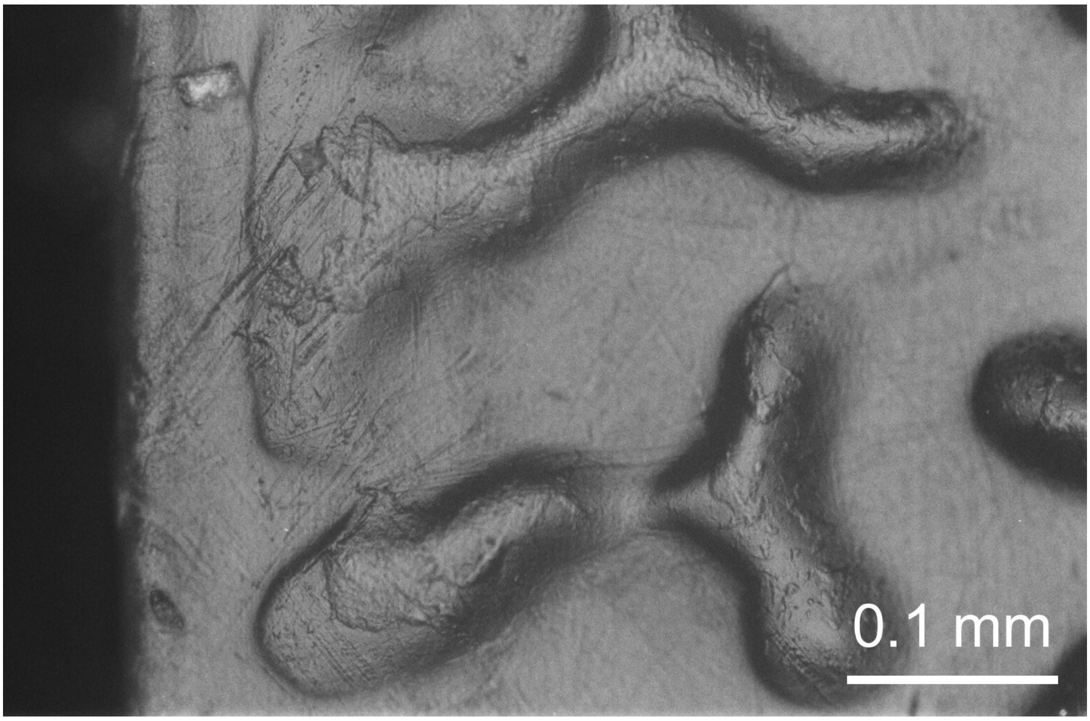


Fig. 4 (b)

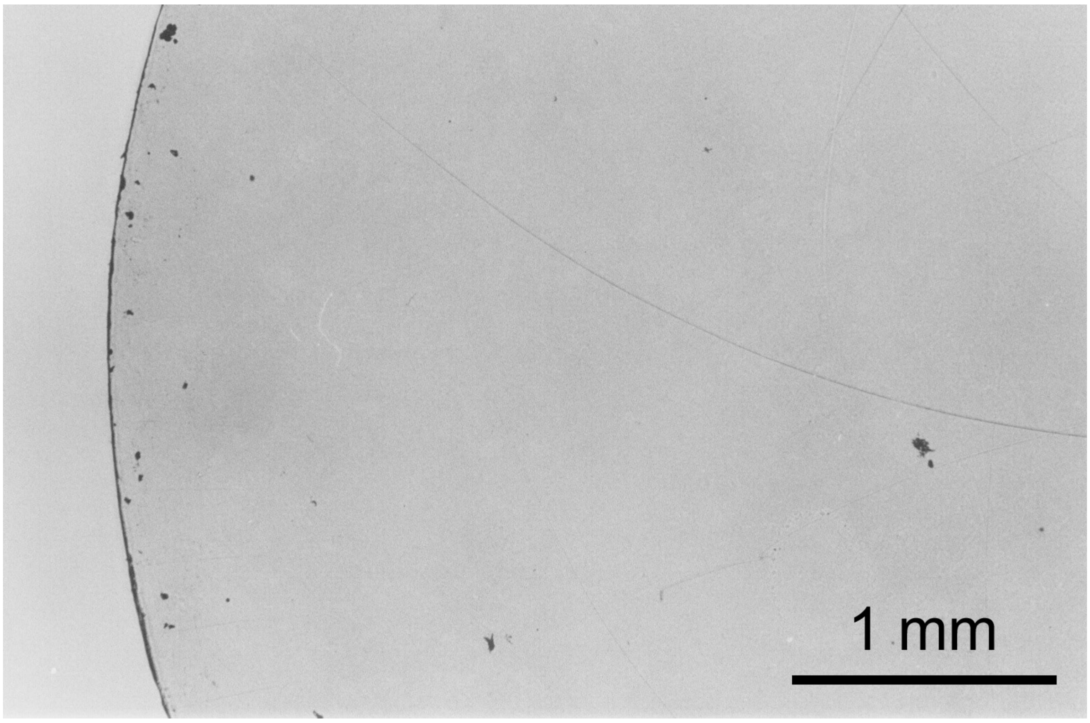


Fig. 5 (a)

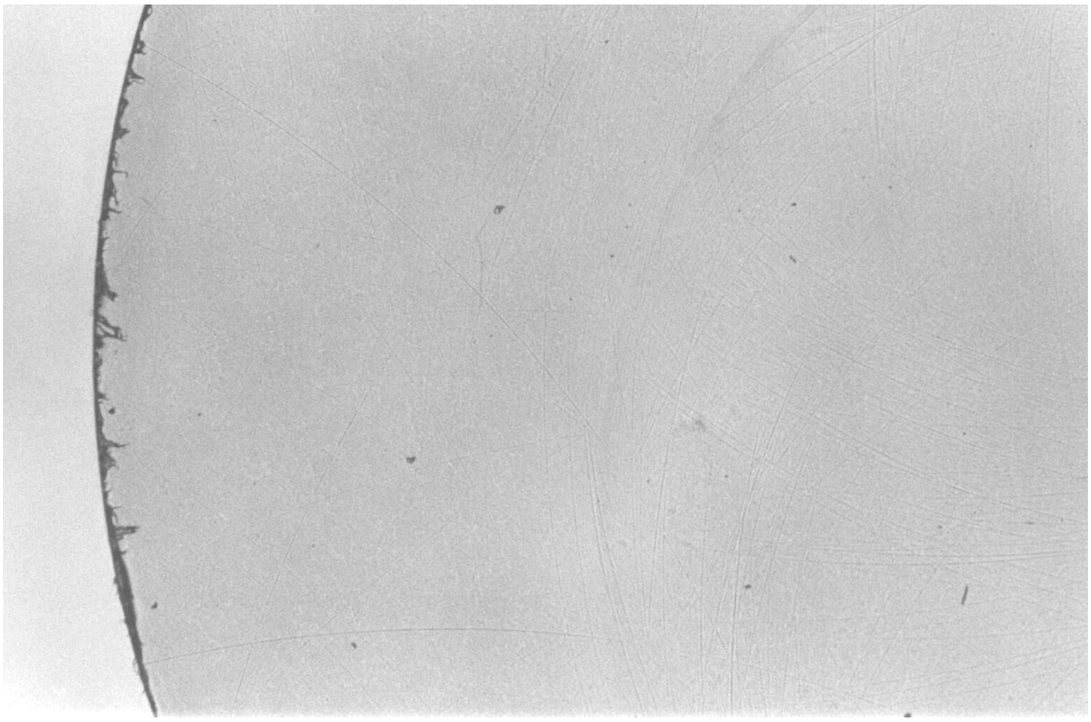


Fig. 5 (b)

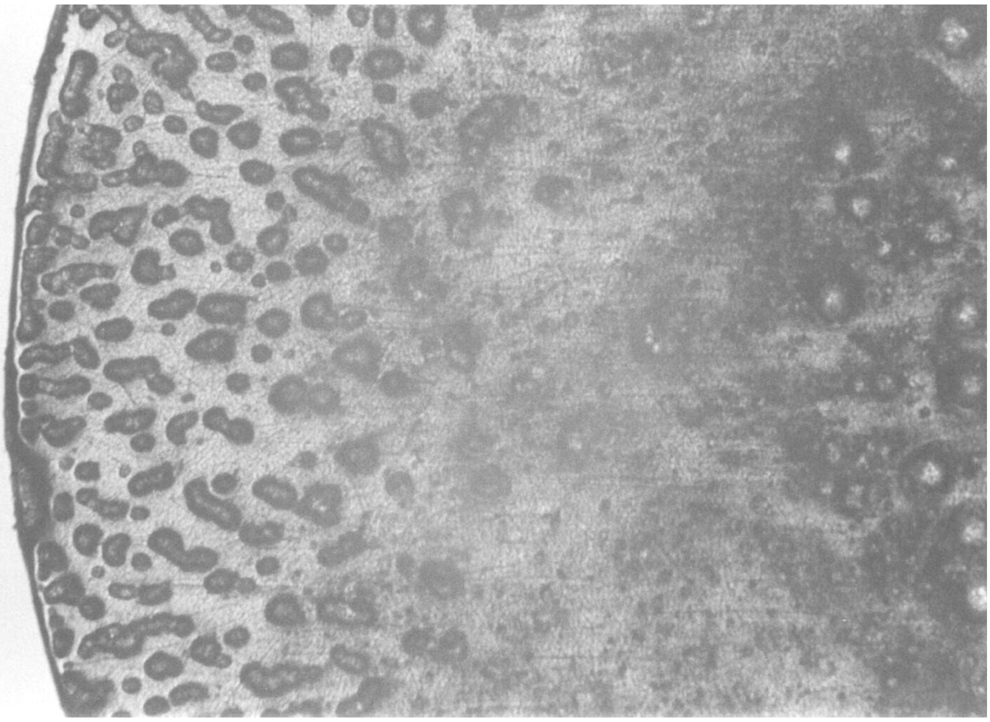


Fig. 5 (c)

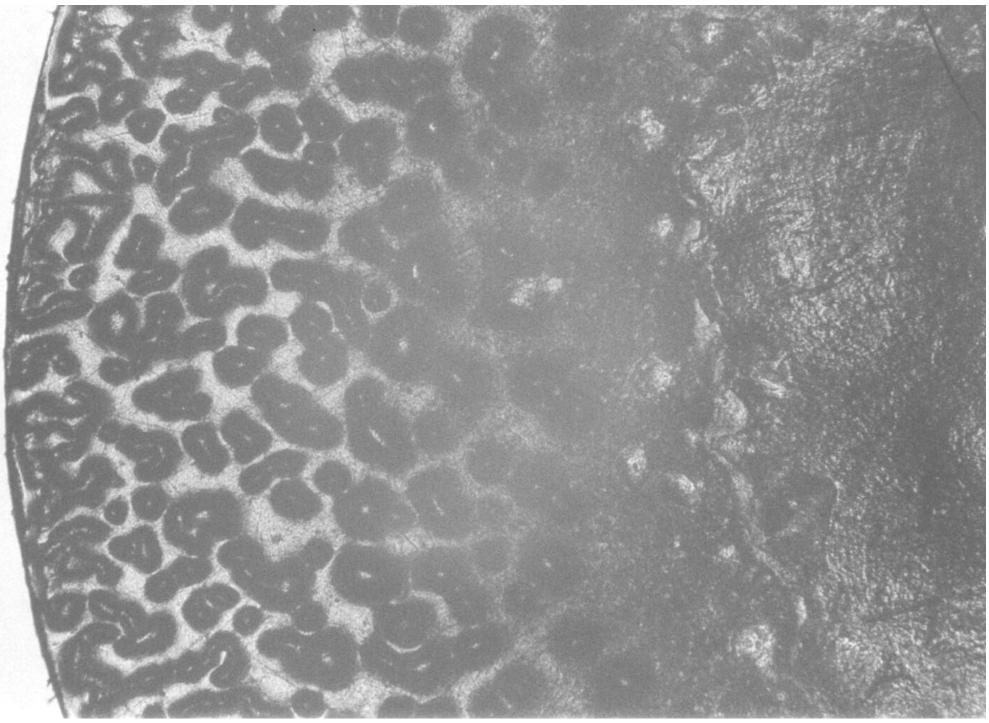
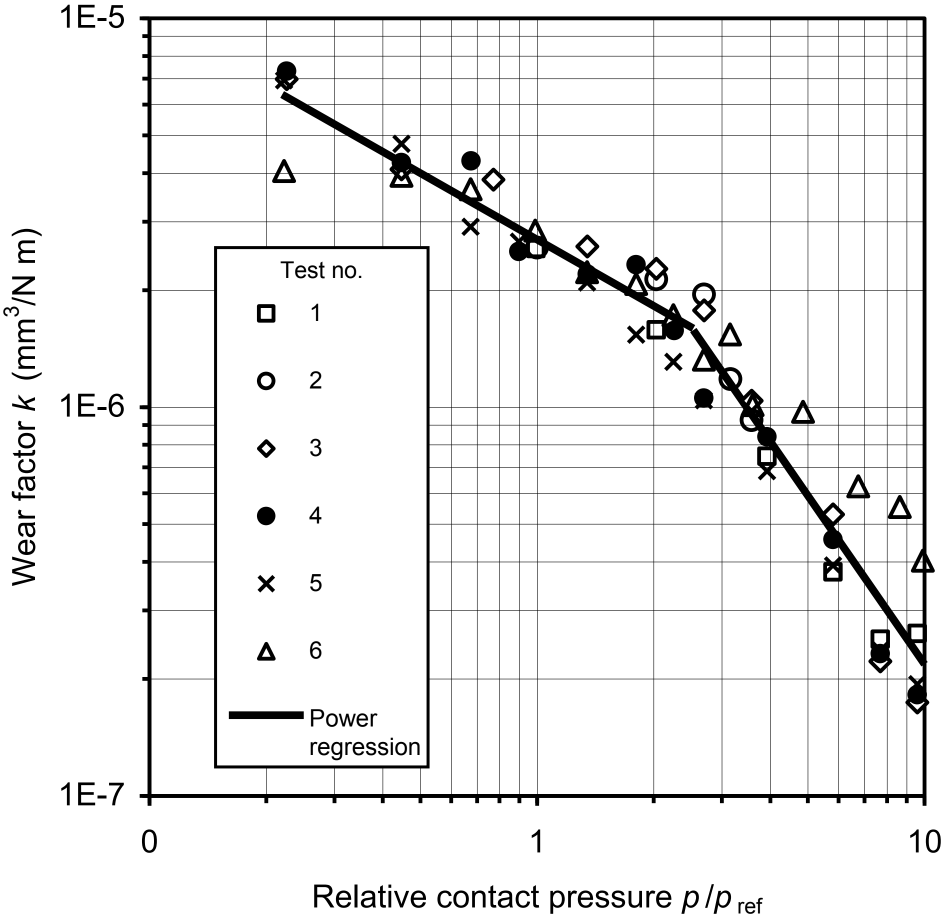
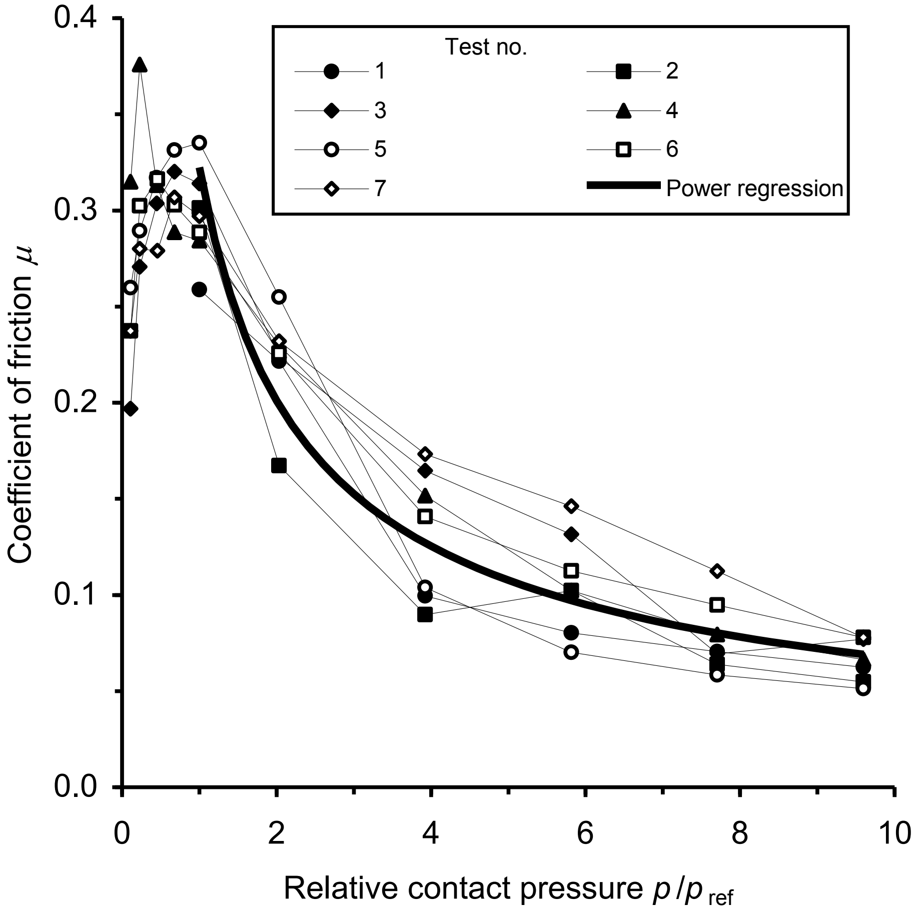


Fig. 5 (d)



1E-5
1E-6
1E-7
Wear factor k (mm^3/N m)
0
1
10
Relative contact pressure p/p_{ref}
Test no.
1
2
3
4
5
6
Power regression

Fig. 6



0.4
0.3
0.2
0.1
0.0
Coefficient of friction μ
0
2
4
6
8
10
Relative contact pressure p/p_{ref}
Test no.
1
2
3
4
5
6
7
Power regression

Fig. 7